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Vibro – acoustic failure recognition on combustion engines at the end of assembly lines

Abstract: The main objective of the combustion engines testing at the end of production line is to ensure that manufactured products fulfil the strongest quality requirements, by providing precise decision about engine functions, and in case of failure occurrence, localisation of failure and, when possible, failure cause. This paper presents a study of the failure recognition of combustion engines on the end of a production line. The main focus is to present current state of the art functions of the automated end of line test stations (cold tests), possibilities of the failures recognition, methods of the vibro – acoustic data analysis, problems and proposition of the solution. In this publication, possibility of the implemetation of the time – frequency vibro – acoustic data analysis, (wavelet transformation), with the aim of improvement of the failure recognition on the cold test (improvement of the product quality) is described.

Key words*: quality control, combustion engine diagnosis, cold test, wavelet transformation*

Wibroakustyczne rozpoznawanie uszkodzeń silnika spalinowego na linii montażowej

Streszczenie: Podstawowym celem oceny silników spalinowych na końcu linii montażowej jest zapewnienie, że wyprodukowany silnik spełnia wymagania jakościowe (ocena funkcji silnika), a w przypadku wystąpienia uszkodzenia jego lokalizację i jeśli to możliwe jego przyczyny. W artykule zaprezentowano studium rozpoznawania uszkodzeń silników spalinowych na końcu linii montażowej. Do podstawowych zadań należało zaprezentowanie stanu wiedzy dotyczącego funkcji automatycznych testów końcowych tzw. testów zimnych, możliwości rozpoznawania błędów, metod wibroaksutycznej oceny sygnałów, problem i propozycje jego rozwiązania. Przedstawiono możliwość wykorzystania metody czasowo – częstotliwościowej analizy sygnałów (transformacji falkowej) do analizy sygnałów wibroakustycznych w celu poprawy rozpoznawania uszkodzeń silników spalinowych na końcu linii montażowej.

Słowa kluczowe: kontrola jakości, diagnoza silnika spalinowego, test zimny, transformacja falkowa

1. Introduction

The aim of this paper is to study of the failure recognition of the combustion engine at the end of an assembly line (cold test). Manufactured engines have to fulfil high specifications regarding its reliability, low fuel consumption, low exhaust gases toxicity etc. Engine should fulfil manufacturer specifications from begin of its life time. In this connection it is very important for every manufacturer to develop methods of the combustion engine analysis at the end of the production line, which implement full detection and identification of failures. From controlling of production processes point of the view we want to reduce internal costs, improve general quality of the product, reduce guaranty costs and finally improve of the end customer's satisfaction. For controlling of the production processes, methods are required, which enable early detection of the manufacturing problems, having important influence on the functions of the product. Important correlations between design, manufacturing methods on the manufactured engines features like mechanic features, electric features, vibro – acoustic, etc. are to be investigated.

The chance for complex engine quality evaluations in the manufacturing environment provide automated test stations like leak test, cold test and hot test. Especially cold test station enables finding of multiple manufacturing processes related problems.

Applied nowadays analysis methodology, used for evaluation of the vibro – acoustic measurement data incoming to the cold test stations, exhibit some important disadvantages comparing to actually available advanced techniques of data analysis. For example use of the Fourier transformation based methodology for a measured signal causes loss of the essential information about a particular time of the occurrence. For more precise and reliable analysis of the vibro - acoustic signals on the cold test, wavelet transformation will be investigated. Wavelet transformation example will be presented on turbocharger failure recognition problem. Turbochargers will be measured at the end of production line, on the cold test.

2. Quality assurance of combustion engines at the end of line tests.

End of line control has to provide, that manufactured engines that are leaving factory assure all of the specifications (no manufacturing failures) required by the national and international institutions, engine receivers (car assembly factories and clients). In this situation we strive to eliminate the maximum of assembly and manufacturing failures. The assembled engine is analyzed at the end of line using different control stations (see Fig. 1). At the first control stage comes leakage test in which we can prove if assembled engine has any leakages (for example if exist some leakages on the alloyed block casing).

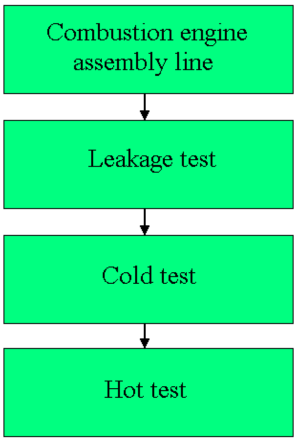

Fig. 1. End of line assembly testing of internal combustion engine

Second control stage is a cold test, where engine is tested under conditions without combustion process. Engine is driven with asynchrony electric motor. During this test we can evaluate assembly and manufacturing processes objectively. Evaluation of the engine can be divided into sections like mechanical test, electric test, leakage test, injection system test, mixture test vibro - acoustic test etc. The last step of the engine analysis at the end of the assembly line is so called hot test. Engine is tested under combustion conditions. We can test such parameters as exhaust gases composition, torque etc. Because of the very strong influence of the noises (caused mainly by the combustion process) on the output measurement signal, we have limited chance of recording failure states generated by the engine (subtle signal features in comparing to surrounding noise).

3. Evaluation of the combustion engine on the cold test

Cold test is a test station being used at the end of the assembly line to control assembly – manufacturing processes. The sensors used to collect measurement data and simple signal analysis methods allow evaluating functions of the engine assembly (see Fig. 2). At first we are able to evaluate correctness of the mechanical functions, by analysing of the oil pressure (dynamic and static), shape of the torque curve, sensors and actuators tests etc. On the other hand it is possible to perform next leakage tests e.g. cooling system, oil cavity test, fuel system etc.

Vibro - acoustic analysis used on the cold test ensures recognition of the wide spectrum of the assembly – manufacturing failure states. It allows partial failure recognition of the unwanted noises, vibrations, mechanical defects, irregularities in work cycle caused by a wrong assembly process. Simultaneously it is possible to find lots of the defects caused by faulty manufacturing process (e.g. bad tooling, alloying or other process). Currently it is possible to recognise multiple number of ICE failures on the cold test as a for example lack of the crankshaft bearings, unbalances on crankshaft and camshaft, failures on the cog wheels (tooth failures), steering chain drive failures (tooth damages, noises etc.), valve failures (irregular work) etc. More information about failure identification possibilities can be found in papers [1][2][3].

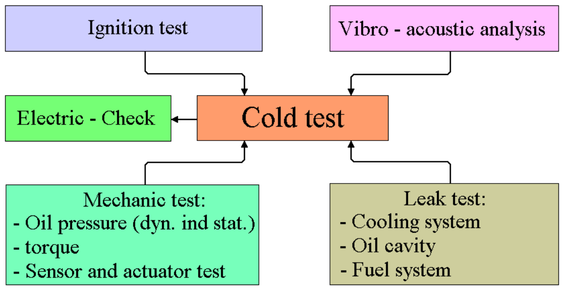

Fig. 2. Cold test functions

Received vibro – acoustic signal can contain not only signal elements generated due to nearest kinematics links but also other components transmitted thru the body structure (generated by other kinematical links). From the vibro - acoustic quality control point of view, collecting of the all information's about engine is very difficult and in many times almost impossible because of the complexity of the assembly processes of the particular parts and engine components. Currently implemented measurement systems, used for the quality control of the produced combustion engines can be treated as a modification of the very effective gear control system. Control tools used for gear diagnosis are based on the time signal analysis, frequency analysis (FFT methods) and order analysis. As a basis for this analysis is the assumption that gear noise is a sum of the particular mechanic component noises. Having knowledge about shifts (transfer) of the analysed parts it is possible to extract information about individual noises features. For precise analysis of the measured signal, method of the analysis of the noises with synchronisation to the main shaft rotation (acoustic stroboscope) is used. Afterwards, measured signals for every shaft are being amplified to show low energy failures components. Resulted signals, (for separated channels), can be processed using different methods of analysis as for example FFT, order, minimum, maximum etc. Obtained values are being compared with boundary values. Boundary values are created in learning processes (evaluation of the defined number of the analysed items). For this purpose, well - known statistic methods of the measurement data analysis are used. We can define such boundary values as: single peak values boundaries, statistic parameter boundaries such as average ± average deviation. Creating of the borders is crucial due to quality control task. Very important for the reliable failure recognition is the shape of the tolerance boundaries for controlled engines. Wide boundaries can be cause for a overlooking of the failures and tight can cause a great amount of pseudo failures.

For analysis of combustion engine at the cold tests techniques based on the crankshaft angle representation of the measured signal and order analysis technique are used. Vibration data is measured with corresponding tacho signal for crankshaft and for camshaft. For constant crankshaft velocity level (input value), the separation of the single rotations and connected vibrations is made. In the following step vibrations averaging for engine work cycle is made. Measurements are being analysed in time, angle, frequency and order domain. Specific harmonic components of the signal are being searched (order analysis, main frequency is the crankshaft frequency). Afterwards, tolerances boundaries (minimal and maximal value) are created based on the statistic features of the signal. If the current value of the analysed signal exceeds the values for the selected boundaries (in one or more windows), this state can be called as a failure state. Defected engine will be delivered to the reparation station, where the engine will be searched for failure cause and failure part or module will be changed. Then the engine will be delivered back to the cold test station. Engine will be approved for assembly in the car if it accomplishes all of the requirements set on the cold test.

4. Proposed method of the vibro - acoustic data analysis (cold test measurements example) Wavelet transformation implementation examples for ICE analysis.

Wavelet transformation is highly adequate tool for analysis of non stationary signals. Wavelet transformation, in comparison to Fourier transformation based methods, permits analysis in time - scale (inversion of frequency) domain. This method enables a better frequency resolution for short signals (high frequency components) and better time resolution for long signals (low frequency components).

There are multiple different non stationary effects, which can occur in working ICE (either in firing or trailed conditions). After [4] we can say, that internal combustion engine depending on its operating condition can be source of non stationary vibration signals. Causes of the non stationary signals components include occurrences of the nonlinear phenomena induced among other things by clearances or nonlinear characteristics of elastic components [4]. Frequency characteristics of signals essentially depend on transmittance of the propagation route of component signals from their source to the measuring point. We can distinguish change over state in engine starting phase [5], combustion process induced non stationarities [6] , valve system vibration phenomena [4], piston - cylinder assembly vibrations [7], cogwheel vibrations problems [8] etc. In the last years time - frequency (TF) analysis methods have been used for investigations of knocking combustion in the Diesel engines (knock recognition). Objective was improvement of combustion process (better control of the combustion processes in the cylinder space) and therefore reduction of the toxic exhaust gases, reduction of fuel consumption, reduction of engine wear etc. One of the many problems, which have been analyzed with WT is valve system vibration phenomena. During opening and closing of the valves transient vibrations can be produced. This vibrations are difficult to analyze within frequency methods. In [4] WT have been used for investigations of the valve system vibrations changes being cause of different valve system failures. To describe failure in the valve system (damage of the exhaust valve), in [4] time energy density analysis approach based on wavelet transform have been used. Another interesting problem analyzed recently is piston - cylinder assembly vibrations. In standard ICE, pistons create strokes while changing their motion direction. The force depends crucially upon the clearance between piston and cylinder wall [7]. Reduction of the clearance in the piston - cylinder assembly have been made by changing old worn pistons by new ones. For analysis of the resulted signals Continuous wavelet transformation (CWT) and Hoelder coefficients has been used [7]. Hoelder coefficients were useful for discrimination of the failures in the piston - cylinder assembly Wavelet transformation (CWT) has been also used for identification of the intern leakages in the intake manifold [9]. For diagnostic purpose averaged wavelet power spectrum have been used. Energy of the of the CWT increase in cause of the intake manifold intern leakages [9].

The objective of this paper is presentation of the method for a vibro – acoustic data analysis, which can be used for failure recognition at the end of line test stations (cold test) in case of non stationary problems. To determine potential failures states occurring in the assembly process and occurring by the customers failure mode effect analysis (FMEA) has been used. One of the critical parts, which has been revealed from the FMEA is turbocharger.

Based on the literature research it can be concluded, that time – frequency analysis methodology and especially wavelet transformation have not been yet implemented for analysis of the vibro – acoustic processes occurring in the ICE turbochargers. Turbocharger noises like whistles are one of the most relevant reasons for the reclamation of the customers cars. Whistles occurs in run – up condition (non stationary conditions) and can be caused by the different manufacturing related problems like blade defect, unbalancing, defected turbocharger bearing etc.

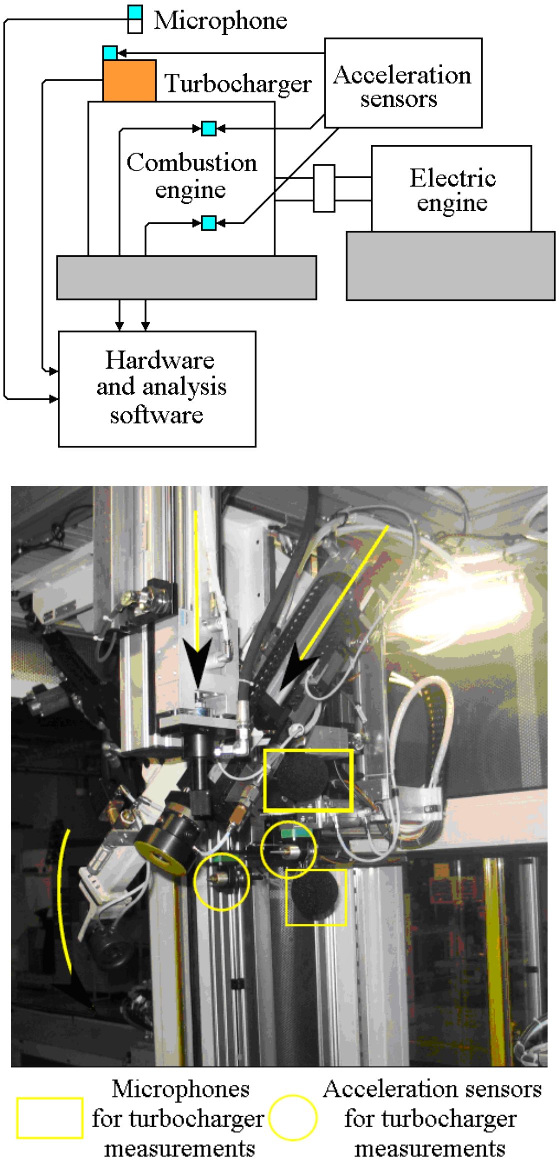

Fig. 3: Vibro – acoustic cold test measurements (top figure) and turbocharger measurements set – up (down figure)

Investigations on defected turbochargers have been performed on 2,0 dm^3 common rail engine (81 kW, without balance shaft module). Assembled common rail engine was analyzed at the "‘end of line"’ test stations. Engines with prepared failures have been measured on the cold test with three acceleration sensors at different positions (cylinder pulley, cylinder head and turbocharger), microphone (turbocharger) and two velocity sensors on the crankshaft and camshaft (see Fig. 3).

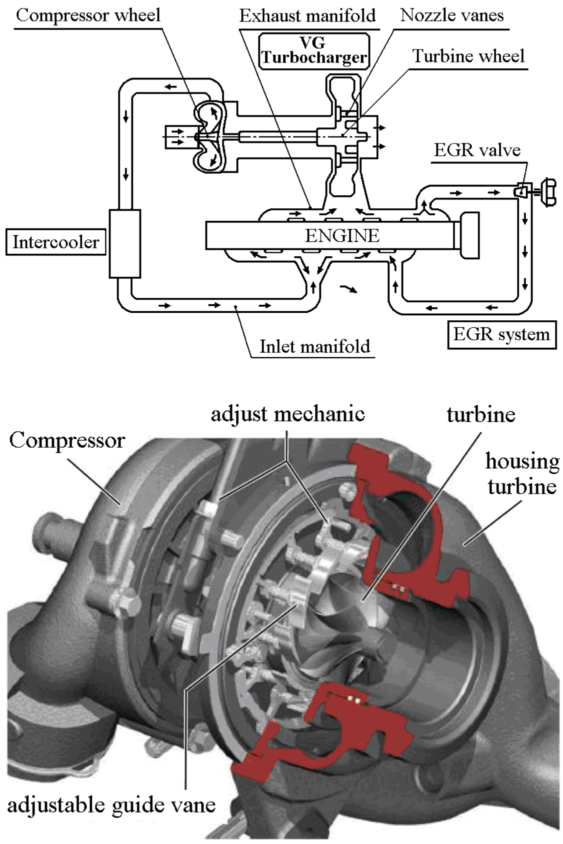

Fig. 4: VG turbocharger and EGR [10] (top figure) and VTG turbocharger inside view [11] (down figure). The amount of EGR can be controlled properly since the exhaust pressure is adjustable by opening and closing the nozzle vanes [10]

Turbocharger (see Fig. 4) vibrations and noises were measured for 500-3000 rpm crankshaft run-up and for constant 3000 rpm (see Fig. 5). Resulted signal has been analysed, at first, for a constant velocity level and afterwards for the engine run – up. Time – frequency analysis method, wavelet transformation (wavelet packet analysis), has been used to process measurement data (good engines and engines with failures). Engine vibration data has been resampled to the single engine cycle. For this new data set wavelet packet transformation (for a selected mother wavelets set and decomposition level), has been performed. Example of wavelet packet transformation based frequency decomposition has been presented on the Fig. 6

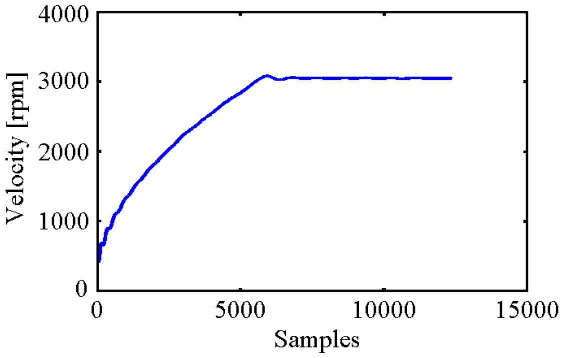

Fig. 5: Crankshaft rotating velocity curve observed during cold test measurements

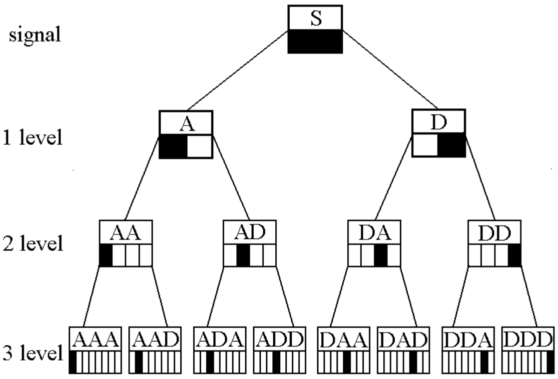

Fig. 6: Three level decomposition example based on wavelet packet transformation

To fulfill high quality requirements of produced internal combustion engines, adequate testing conditions and adequate engine testing methodology are required. On the production test stands like cold test reproducible environment (negligent small variation of steering and observed parameters, negligent small environmental noise) can be mostly assured. Other more specific requirements are precise velocity measurements, correctness of the engine itself (no internal gases leaks in the engine, imprecise timing of the valve system, no leaks in the turbocharger and its peripheries are allowed).

Today recognition and identification of the turbocharger vibro – acoustic failures not only on the production test states but also in the customers cars, is mostly performed with help of order analysis in the run-up phase and is presented in form e.g. of the Campbell diagrams. Analysis of the turbocharger noises will be usually performed on the run-up acoustic signals. In the run-up conditions most common noises types like turbocharger "‘whistles"’ will be revealed. With use of the order analysis turbocharger failures like unbalance, changed turbine geometry, mechanical failures on the turbocharger can be recognized.

Explanation of the turbocharger diagnosis problem will be made on example of unbalanced turbocharger main shaft module. For purpose of turbocharger unbalance investigations unbalance measurements have been performed on the "‘two planes"’ balancing device (measurements on compressor wheel and nut) for selected, correctly assembled and balanced turbochargers. Finally unbalance values have been intentionally increased (see Table 1), so that transgression of the border values (border value assumpted by the engine manufacturer) occurs.

To avoid multiplication of the costs for testing of the failures possibilities on the engine, specific mapping researches were made on a single test engine called from now as "‘old engine"’. Collected measurement were at first analyzed in respect of valve system propriety, and leakages of turbocharger. For investigation purposes three investigation set-ups have been prepared. First set-up build turbochargers without failures mounted on the new engine, second new turbochargers mounted on the old engine and third turbochargers with failures mounted on the old engine. During investigations four different vibro- acoustic signals have been collected. Parameters like pressure in the turbocharger, inlet pressure in the cylinders, outlet pressure from the cylinders have been observed additionally, with use of standard cold test software, with objective to identify other parameters relevant for the failure recognition.

Table 1: Rest unbalance values for good and intentionally unbalanced turbocharger.

Rest unbalance values	Nut [mgmm]	Wheel [mgmm]
For good turbocharger	35,5	31,9
Changed unbalance values	72	54

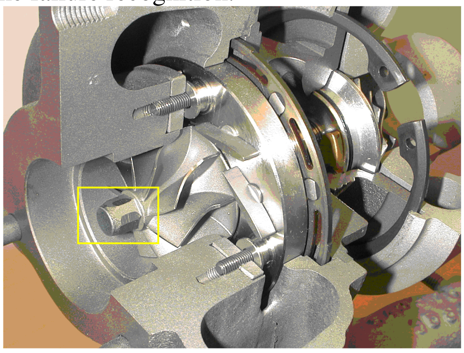

Fig. 7: Turbocharger with marked place of balancing

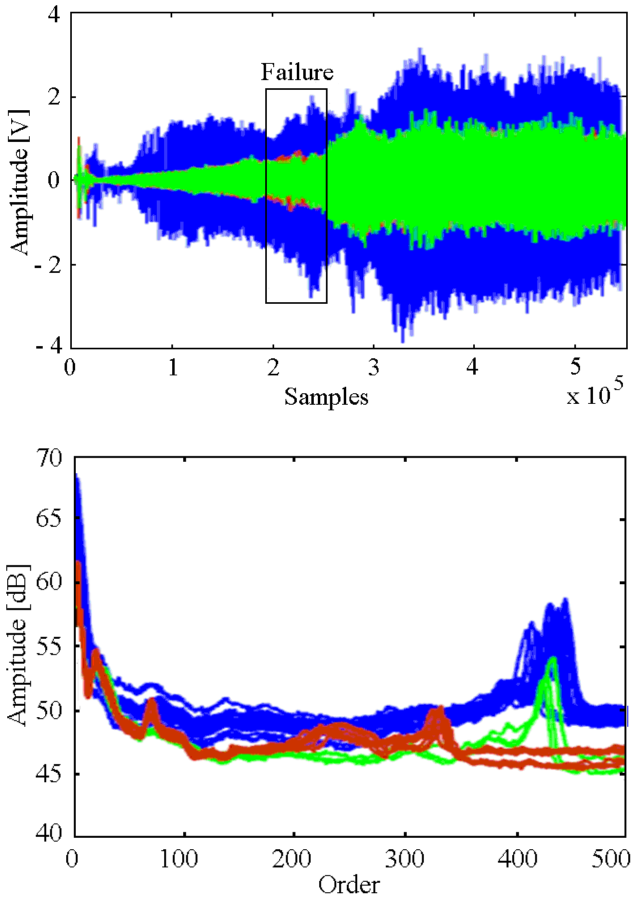

Fig. 8: Time (top figure) and order analysis (down figure) for: good turbocharger in old engine (green line), bad turbocharger (red line) in old engine, good turbocharger in new engine (blue line). Orders are created by division of collected vibro – acoustical frequency spectrum by the reference crankshaft frequency

For failure identification purposes, diagrams of the acoustic signal both in the time domain (Fig. 6 top) and in order domain (Fig. 6 down) for three set-ups have been presented. Turbocharger main shaft unbalance induce acoustic change in the time domain signal. This difference, in comparing to the good turbocharger signal, can be observed predominantly in the run - up measurements results. Time signal evaluation will not be useful both for failure detection and identification purposes. With help of the order analysis relevant failure related orders can be distinguished According to presented diagrams, identification of the failure occurrence can be difficult, whenever refurbished engines and good new engines will be compared. In consequence failure could remain not detected. In cold test practice group of the good "‘new"’ engines will be always used to define class of the good engines. Objectives is recognition of the turbocharger failures for different in non stationary conditions (run - up phase) within wavelet packet transformation and identifications of the features describing different failure causes independent of the investigated engine set (new or refurbished engine). Collected vibro - acoustic signals have been analyzed with use of standard cold test station software (based on the order analysis) and afterwards in off - line modus with wavelet packet analysis. Main objective was finding of clear differences between good and failure turbocharger state (evidence of failure) under consideration of dispersion of the series measurements results.

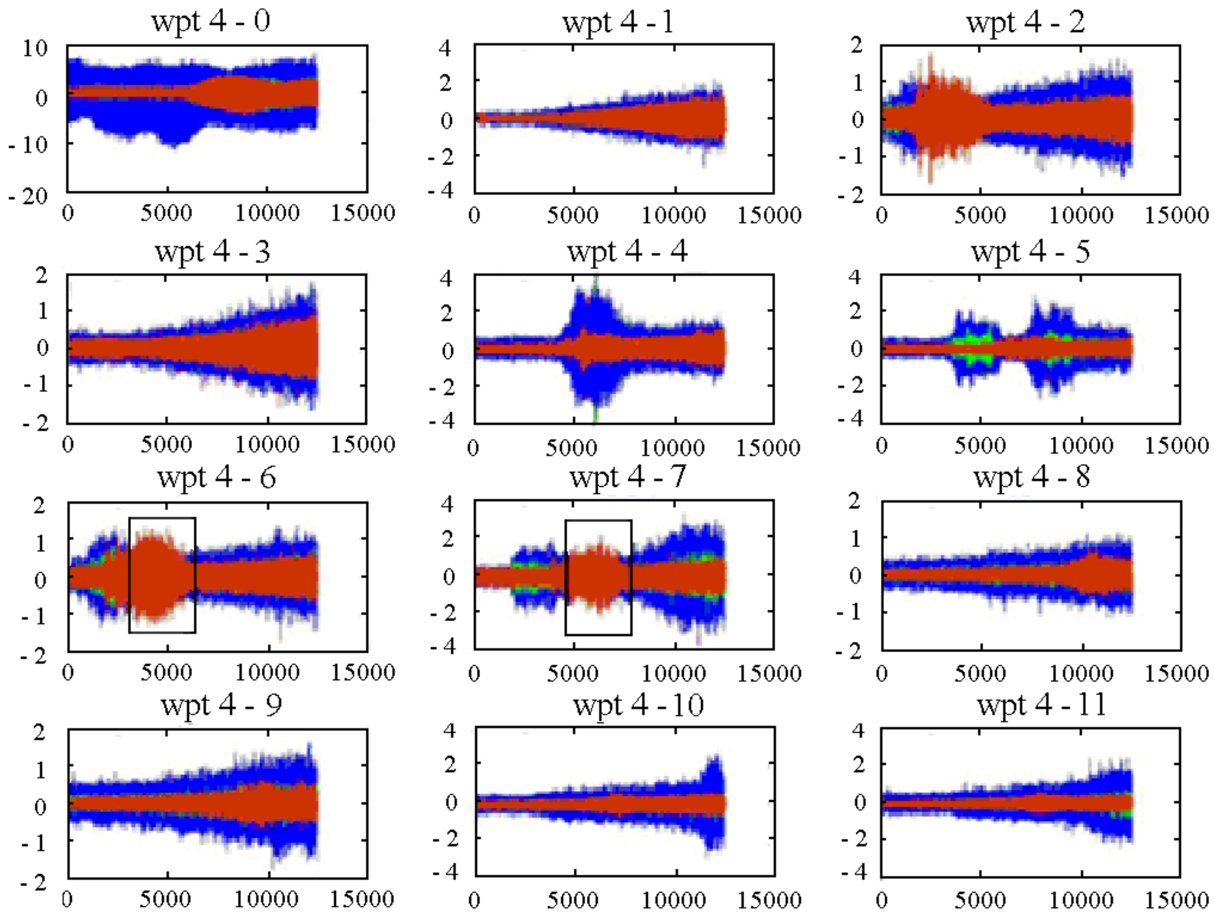

Fig. 9: Comparison of the Wavelet Packet decomposition for good and failure turbochargers: wpt 4-0 (upper left) to wpt 4-11 (bottom right) (decomposition depth 4, db8, run-up): good turbocharger sound for new engines (blue), good turbocharger sound in old engine (green), unbalanced turbocharger (red). Horizontal axes represent number of samples, Vertical axes represent amplitude [V] of the transformed signal

Finally reliable, failures specific features have been searched. The turbocharger sounds will, in usually, occur in the engine run - up phase. To distinguish influence of the turbocharger unbalance on the sound in the run – up phase analysis of turbocharger sound signal for 500 - 3000 has been performed. Run – up signals have been individually analyzed to discover failure related, robust features. The wavelet packet transformation terminal nodes were afterwards compared for good and false turbocharger. On the Fig. 9 coefficients for different fourth scale terminal nodes for good new engine (blue), old, refurbished engine without failure (green) and old, refurbished engine with failure (red) have been presented. Based on this representation clear differences between good and unbalance state of the turbocharger, tested in the run - up phase, can be found in nodes 4-6 and 4-7.

In comparison to the order analysis, wavelet transformation based evaluation of the turbocharger noises, allows precise discrimination between good and failure state. For that reason wavelet transformation based evaluation should support end of line testing of the turbocharger. It has shown promising results by the comparing of set of good and bad engines. Interesting conclusion is that whistle noises measured on the failure turbocharger, assembled into the old research engine, can be recognized easily even in case when for definition of reference cases, only new engines will be used. In this case order analysis based references have been insufficient to recognize failures.

6. Summary and Conclusions

In this paper the study of the failure recognition on the end of the assembly line (cold test) and especially study of methods for vibro - acoustic data analysis on cold test have been presented. The method of turbocharger evaluation based on the time – frequency analysis (wavelet transformation) has been discussed. In comparing to order analysis based analysis methodology defected turbocharger can be precisely identified. Additionally with use of the wavelet transformation to the turbocharger diagnosis no expensive velocity measurement equipment is necessary for measurements of the compressor wheel velocity (e.g. laser measurement equipment).

Controlling systems at the end of the assembly line don't provide programs like expert systems which help by fast identification of the failures and its causes and reduce the time of the parts analysis, supporting training of the new workers (reduction of the training times) etc. For precise definition of the failure cause, knowledge, experience of the operating personnel is needed, supported by the suitable representation of the measured information's. Up till now, some methods of signal classification, based on the neural networks, have been used to analyse combustion engines at the end of line tests. These methods have not been successfully implemented because of the low efficiency for small subsets of training data (variations of the feature sets) and low transparency of the methods (black box). These limitations have prevented precise, automatic discovery of the failure and its cause. In the future it is to be investigated how precise different failures can be automatically detected in the end of line environment (on the cold test).

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